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BACKUP STRATEGIES FOR MARS LANDING

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Abstract

Entry, descent and landing (EDL) is probably the most difficult and risky phase of a human mission to Mars. It is in general acknowledged that once the vehicle enters the atmosphere, there is no abort to orbit option, the vehicle must land on the surface. Whatever the EDL systems for Mars, the qualification might be very difficult, very expensive and the risks could still be very high, especially for the first missions. Risks could nevertheless be mitigated if backup options existed during the last phase of EDL. If an important problem is encountered during the last minutes of the descent, a possible option is to eject the astronauts and to use individual parachutes for braking. Considering the density of the atmosphere and possible parachutes diameters, parachutes are not sufficient to land safely on Mars. It is therefore proposed to add small propulsion systems, which could be attached to the seat of the astronaut. The feasibility of that proposal is examined. In the event of an emergency landing, the astronaut will still have to reach the base quickly to survive because of his limited oxygen autonomy. An automatic rover can be sent to increase this autonomy and potentially facilitate the repatriation of the astronaut. If he is able to move, the astronaut will be able to choose to get closer to the base or to the rescue by himself. This choice will be motivated by the astronaut's ability to determine the state of his resources, his ability to move and the path to take.

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Keywords: Entry, descent and landing, backup strategies, landing risks.

1. Introduction

As entry, descent and landing (EDL) on Mars is one of the most dangerous phases of a human mission to Mars, is it necessary to integrate back-up systems to reduce the risk of losing astronauts [1] ? To our knowledge, this problem has never been addressed before. On Earth, the launch and access to orbit phases, which require heavy and complex propulsion systems are considered very risky. In order to mitigate the risks, the human rated qualification rule is to provide an emergency evacuation system that can be triggered at any time for a safe return to the ground under parachutes. For the return from Earth orbit, no emergency system is available, apart from the redundancy of the parachutes, but there is however no need for a propulsion system (except during the last second for the final cushioning). As the atmosphere of Mars is much thinner than Earth's, a propulsive phase is required for the last braking and as the surface is irregular, the propulsive phase might involve lateral moves as was the case for the Apollo 11 mission to the Moon. The complexity of the EDL phase for Mars is therefore much stronger than Earth's and the inclusion of a backup system for landing is an important issue. However, it is well known that the total mass of any landing vehicle is critical and there are very few margins for other equipment. Any backup system must be very light. During Gemini missions, astronauts were equipped with a parachute and could eject [14]. Likewise, when the Hermès shuttle was designed, seat ejection systems were planned, similar to those used for military airplanes [5,16]. Is it possible to use ejection seats for Mars landing? And if yes, what would be the conditions of use and the requirements for complementary systems allowing safe landing and survival after landing? These questions are addressed in the following sections. Section 2, the risks of the EDL phase are summarized. Section 3 is dedicated to the constraints and conditions that have to be fulfilled to enable the rescue of the astronauts. Different rescue systems are proposed and discussed Section 4 and the main conclusions are given in the final section.

2. EDL risks

Numerous robotic missions have been implemented for the exploration of the surface of Mars. Many were successful (Viking, Pathfinder, Mer, Phenix, Curiosity, Insight), but many others failed to reach the surface at the very end of the mission, due to a problem encountered during the EDL phase: Mars 2 (parachute not deployed), Mars 6 (contact lost during descent), Mars 7 (retrorocket failure), Mars Polar Lander (contact lost during descent), Beagle 2 (contact lost during descent), Schiaparelli (inappropriate descent procedure).

If EDL risks are considered very high for robotic missions, it could be even worse for human missions. Many authors highlighted these risks, explaining that landing heavy vehicles on Mars is more challenging than landing light vehicles [1,3,6,7,10,15]. There are several reasons for that:

- The ballistic coefficient is in general higher for heavy vehicles, which means that atmospheric braking is less efficient.
- As the use of gigantic parachutes would be impractical, different EDL systems must be considered for heavy vehicles, for instance giant inflatable heat shields [8], which implies that the Technology Readiness Level is currently very low and the feasibility is still uncertain.
- If very large diameter heat shields are required (perhaps two heat shields, one for hypersonic and another for supersonic regime), a complex deployment procedure has to be carried out.
- At the end of the atmospheric braking phase, heat shields may have to be ejected, which might be difficult.
- After heat shield ejection, the vehicle must be reoriented in a very short time so that the thrust direction is opposed to the speed direction. This maneuver is more difficult and takes longer for heavy vehicles.
- The velocity and the landing position must be controlled with higher accuracy.

All in all, according to NASA, EDL risks are considered a major concern of human missions to Mars and the best option remains to be determined [6,7].

3. Operational constraints for a rescue system

3.1 Life support system

Due to the mass and volume constraints of the emergency evacuation module, it is unlikely that the descent module will be pressurized. If not, it is conceivable that among the elements making up the ejection system is a module that can be pressurized (this can take a basic form such as a tent). With the help of this shelter, if the astronaut can remove his suit, he will be able to repair it more easily but also to care for himself and replace various essential elements of his suit, such as oxygen reserves and carbon dioxide filters. The pressurized shelter also provides water and food supplies outside the suit. Depending on the complexity of the pressurized module, it can be used to manage temperature variations. Indeed, the temperature variations on the surface of Mars are important, going from -125°C to +20°C.

Without this additional pressurized space, the astronaut has to rely only on the resources of the life support system attached to the suit. Currently, the EMU (Extravehicular Mobility Unit, spacesuit used for outside activities on the International Space Station) has an autonomy of about 7 hours [9]. If the suits used on Mars will evolve, with significant improvements on the astronaut's mobility and the quality of the communication systems, the oxygen autonomy should remain similar due to constraints on the size and mass of the reserves. The only accessible food and water reserves are those already present in the suit. Healing and repairing are also harder.

If a base is already present on Mars with other astronauts, communicating with them can be life-saving. Thus, in order to maximize the survival probability, the emergency evacuation module must contain a pressurized module, even a basic one, with additional oxygen reserves, a radio communication system to interact with the base if it is not included in the suit, and medical equipment in case of injuries due to the impact.

In any case, the life expectancy of the astronaut in these conditions is rather small and can be counted in tens of hours maximum.

3.2 Distance to the base

In general, a habitable module is pre-positioned on Mars before the astronauts' arrival. In nominal conditions, there is an accurate control of the descent and the landing ellipse is of the order of 10 kilometers at the end of the aerodynamic braking [17]. According to a NASA study, a lateral displacement of a few kilometers is planned to reach the base in a precise way [7]. If the descent goes badly, but the navigation is correct, the distance of the landing site is thus of the order of 10 km, which seems feasible walking. If on the other hand the navigation is affected, the distance can be enormous, which would certainly condemn the survival astronauts.

The walking speed on Earth is about 5.5km/h. Some research suggests that the optimal walking speed on Mars would be around 3.4km/h [2]. This nominal walking speed would be lower upon arrival on Mars because of the loss of muscle mass during the journey, the rigidity of the suit and the after-effects of the impact. However, a more intense physical training program at the approach of Mars or an integrated centrifuge may limit muscle loss. In addition, certain innovations, such as gradient compression garments [11], can facilitate adaptation. Finally, exoskeletons integrated into the suit [13] can be considered to improve astronauts' mobility.

It is very difficult to predict how all of these factors will affect astronauts' ability to move. However, it is likely that they will be forced to stay on the landing site for some time and that their travel speed will be less than 3 km/h.

Whether the astronaut is able to move or not, the rescue team must come to his aid provided that the distance to be covered remains reasonable. In any case, the teams on earth will not be able to intervene. We must therefore rely on the help available on Mars.

We can imagine several types of vehicles for the rescue:

- An autonomous vehicle allows to bring something to extend the autonomy without being able to transport the astronaut. It can be a pressurized module (if not present in the evacuation module or if it is damaged), oxygen, water, food and possibly a medical kit.
- A self-contained vehicle capable of getting to the landing site, then transporting the astronaut on the way back and extending the autonomy, for example by connecting the oxygen hose to a reserve.
- A vehicle piloted by a remote human, in this case by the astronaut who landed with the back-up system if no one else can do it.
- One can also imagine both modes of operation, autonomous if necessary, or remotely piloted if the astronaut wants to take control, especially if there are obstacles that are difficult to overcome and the astronaut has a better understanding of the terrain and the capabilities of the vehicle.

Provided that other astronauts are already present on the surface, sending an astronaut to rescue another is possible. However, if accessibility is problematic (too far away, or at the bottom of a canyon for example), it means taking the risk of suffering two losses so these survival missions must be validated with the greatest care. One will also be careful about the information that will be communicated to the astronauts already present in the base.

It is conceivable to pre-position an automatic rover ready to leave next to the base and to remote control it (from Earth possibly, via a command not requiring real time) so that it can go and fetch the astronaut.

3.3 Feedback and choice

An astronaut can reach his base only if he has the ability to move sufficiently, in the right direction and in the time allowed by his resources. Depending on his propensity to evaluate these dimensions, the astronaut will have to make a choice between two options:

- Stay at the landing site to take care of himself and wait for help.
- Try to reach the base or a rescue module.

In view of the central role it plays to reach the base in case of an emergency landing or even after exploring the surroundings of the base, special attention must be paid to develop feedback on the three dimensions:

<u>Resources</u>: The design of the interface of the suit and the survival kit can directly integrate this dimension to facilitate reserve calculations. Part of the training must be oriented to allow the astronaut to quickly and efficiently determine the state of his resources.

<u>The position of the target</u>: Ideally a GPS-type tool in which the astronaut has on the same interface his position, direction and the position of his target (whether the base and/or rescue). A satellite can provide such a solution, but it must pass regularly over an area or be areosynchronous. This is the nominal case of NASA missions with the Earth return vehicle waiting on an areosynchronous orbit precisely. A less complete but more reliable solution is the recourse to a visual signal, or in the presence of relief to a transponder placed at the top of a hill and a beacon for the astronaut. For example, the base, the rescuers and the survivor can regularly use smoke to indicate their positions.

<u>The ability to move</u>: This is a difficult dimension to quantify, and the astronaut is the one able to make this estimate. Refining this skill is one of the challenges of training. Knowing that the context (gravity and fitness) during training will necessarily be different on Mars.

It is likely that the choice will be a luxury that the astronaut does not have if the base is too far away or if he cannot move after landing. However, if he has this possibility, it is important to provide a decision aid. Indeed, the astronaut's decision-making ability may be strongly affected by many factors (such as stress, pain and fatigue). Perhaps the software detailing the available resources can include this decision support. If the astronaut is able to establish contact with the base by radio, he or she may also find guidance and comfort. In this case, a detailed map of the landing area may be important to help the astronaut find his way around.

4. Rescue system

As the mass of any complementary equipment is a major concern and must be reduced to the minimum, the simplest and most practical option is to provide ejection seats [16]. This option was already considered and validated for the European Hermes shuttle, which remained a concept study [5]. The idea is to trigger a pyrotechnic system that would open the wall of the space vehicle and allow the ejection of the astronauts on their seats, while they are wearing their spacesuit, portable life support system included, eventually not on their back but attached to the seat. Such an option would be viable only after atmospheric braking, when the vehicle has been slowed down to acceptable velocities. Once ejected, a parachute immediately opens and progressively reduces the speed of the astronaut. On Earth, thanks to appropriate parachute systems (disk gap band parachute), ejection seats can be used at very high velocities, typically around Mach 1 at sea level. On Mars, as atmospheric pressure is much lower, parachutes could be opened at much higher velocities. According to Braun and Manning, on Mars, taking thermal constraints into account, it would be possible to use parachutes at Mach 2.7 or even Mach 3 [1].

However, such parachutes would not be sufficient to reduce the falling velocity to acceptable levels. On Earth, the final (and relatively safe) velocity is between 5 and 8 m/s. On Mars, even if very large parachutes were used, the final falling velocity would be around 50 m/s, which would kill the astronauts at impact.

A propulsion system is therefore mandatory to provide a complementary reduction of the velocity. As it depends on the altitude of the landing site, the size of the parachute and eventually the wind, it is difficult to determine the final velocity and the moment of engines ignition. It is proposed here to follow a similar final landing sequence as that of the Insight mission [4]:

- The ejection seat slows down under a disk gap band parachute.
- At one kilometer altitude (a dedicated sensor is used for real time measurements of the altitude), the velocity is around 60 m/s and it is the moment for parachute ejection and thrusters' ignition. Remark: As the seat can be ejected at lower altitudes, the velocity can be higher. The thrust has to be adapted to the situation.
- Provided that there is still some time before impact, the velocity is decreased to reach 5 m/s at 30 meters above the surface.
- The velocity is decreased to reach 1 m/s at 5 meters above the surface (it was 2.2 m/s for Insight).
- The velocity is kept constant until the surface is reached about 5 seconds later.
- Thrusters are turned off at touchdown.
- Automatic rovers are sent to the landing site to rescue the astronauts.

Importantly, if the seat is ejected very late, the survival of the astronaut would depend on the maximum thrust of the engines and the human ability to support the load of the acceleration. In NASA reference missions, a 4G acceleration is mentioned as a maximum for the design of the EDL systems [7]. It is proposed here to use this constraint to determine the limits of initial conditions to have enough time for slowing down before reaching the surface. Assuming a constant 4G deceleration using the thrust of the engines, the minimum altitude only depends on the initial falling velocity. It is defined by equation 1 and is plotted Figure 1.

$$A_{min} = -0.5(a - G)t^2 + V_0 t \qquad (1)$$

With a: engine acceleration

G: Martian gravity

V_0: Initial velocity

A_{min}: Minimum altitude to avoid the crash

$t = \frac{V_0}{(a-G)}$ (time to reach the ground with V=0)

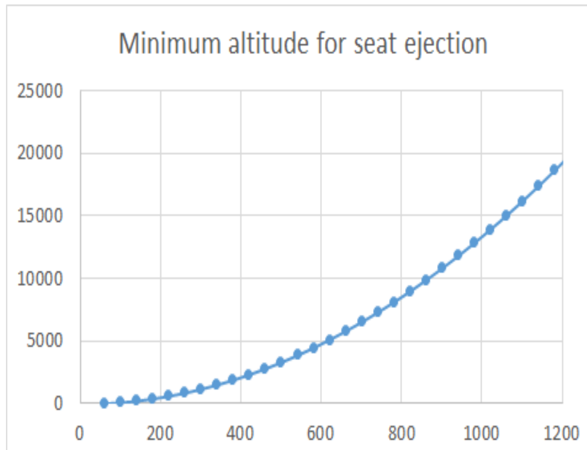

Fig. 1. Minimum altitude for seat ejection (vertical axis in meters) as a function of initial falling velocity (horizontal axis in m/s).

The horizontal velocity is not taken into account in the previous calculation. Let us assume that Mach 3 is the maximum viable velocity for triggering the ejection of the seat. Two cases have to be examined, with or without parachute:

- Without parachute, provided that the altitude is high enough, starting at 1020 m/s, the 4G deceleration would last 32 seconds to slow the vehicle down to 0. This duration can be used to determine the maximum amount of propellant required for the descent. Assuming a specific impulse of 230 seconds (based on the thruster used for the terminal descent of the Insight mission [4]) and a landing mass of 247 kg (see Table 1), the mass of propellant is given by equation 2 (derived from Tsiolkovsky equation) and would be equal to 141 kg.
- Using a parachute, the deceleration would not be linear. Let us assume that it would nevertheless be acceptable in the worst case

scenario, at least until Mach 1 is reached. Then, using thrusters for the terminal braking phase, 41 kg of propellant would be enough if the deceleration is linear and equal to 4G (equation 2). As a parachute is a light device, the parachute option is therefore much lighter than the no parachute one.

$$m_p = m_f e^{\frac{\Delta v}{I_{sp}}-1} \qquad (2)$$

With m_p mass of propellant, m_f final mass, I_{sp} specific impulse and ΔV the velocity change requirement.

Table 1: Mass budget.

Astronaut		100 kg
Spacesuit, LSS included		60 kg
Rescue system	Ejection seat	30 kg
	Parachute	20 kg
	Thrusters	20 kg
	Propellant	41 kg
	Tanks	4 kg
	Margins	20 kg
	Total	135 kg

As the mass is a critical parameter, the parachute option is proposed here. In order to minimize the risks of tilting at touchdown, the seat can be equipped with legs that would be deployed during the descent. The total mass of the system, seat, parachute, thrusters and propellant would be around 135 kg. See Table 1 for a detailed budget mass.

5. Conclusion

A rescue system has been proposed to reduce the risk of crew loss during the descent and landing phase of a human mission to Mars. It is based on an ejection seat for each astronaut, a parachute and a small propulsion system for the landing on the surface. For a successful rescue, the astronauts must wear a spacesuit with full life support and surface rovers must be present on the surface with automatic driving abilities to reach them, provide complementary life support and transport them back to the habitable module. Special attention must be paid to interface design and astronaut training so that the astronaut is able to efficiently evaluate the available options.

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